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Age-Related Differences in Processing Dynamic Information to Identify Vowel Quality

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This study examined age-related differences in the use of dynamic acoustic information (in the form of formant transitions) to identify vowel quality in CVCs. Two versions of 61 naturally produced, commonly occurring, monosyllabic English words were created: a control version (the unmodified whole word) and a silent-center version (in which approximately 62% of the medial vowel was replaced by silence). A group of normal-hearing young adults (19–25 years old) and older adults (61–75 years old) identified these tokens. The older subjects were found to be significantly worse than the younger subjects at identifying the medial vowel and the initial and final consonants in the silent-center condition. These results support the hypothesis of an age-related decrement in the ability to process dynamic perceptual cues in the perception of vowel quality.

KEY WORDS: silent-center vowels, dynamic acoustic information, age-related changes in vowel perception

Increased difficulty in speech comprehension commonly occurs as a function of aging (see Working Group on Speech Understanding and Aging, 1988). This problem may be exacerbated by such factors as noise (Dubno, Dirks, & Morgan, 1984; Gelfand, Ross, & Miller, 1985; Helfer & Wilber, 1990) or reverberation (Helfer & Wilber, 1990; Nabelek, 1988; Nabelek & Robinson, 1982). Many of these difficulties may be explained in terms of hearing loss found in the older population (Bergman, 1980; Corso, 1977; Marshall, 1981). For example, van Rooij and Plomp (1990) found that loss of high-frequency hearing sensitivity with age accounted for almost two-thirds of the systematic variance found in a set of speech perception tests given to a group of older adult listeners. However, it is clear that a portion of these difficulties may be related to cognitive factors that are not strictly sensory in nature, including subject motivation, fatigue, decrements in memory capacity or processing, and higher level linguistic processing (Working Group on Speech Understanding and Aging, 1988; van Rooij & Plomp, 1990). For example, several studies have reported age-related declines in consonant perception in the absence of pure-tone hearing loss in quiet and in noise (Dubno et al., 1984; Elliott, Busse, & Bailet, 1985; Gelfand, Piper, & Silman, 1986).

One possible factor in the age-related decrement in speech understanding may be a decreased ability to process auditory information that changes dynamically in time—an ability that is crucial to the recognition of many phonetic segments. For example, Dorman, Marton, Hannley, and Lindholm (1985) found an age-related difference in the identification of a two-formant [bɑ]-[dɑ]-[gɑ] continuum that varied in terms of the starting point and direction of the second formant transition (there were no release bursts, and the only cue to place of articulation was the second formant transitions). Both normally hearing and hearing-impaired older adult listeners experienced difficulty in identifying these CV tokens, compared to young adult listeners. Gelfand et al. (1986) examined consonant recognition using the Nonsense Syllable

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Test (NST) (Resnick, Dubno, Hoffnung, & Levitt, 1975). Their study found decreased consonant recognition ability in older adults, although the pattern of confusions was similar to that of younger adults. There was a large number of place errors and, in particular, a high proportion of [f] and [θ] confusions. Harris (1954) found that the distinction between [f] and [θ] was cued by information in the vocalic portion of the syllable (i.e., the formant transitions into a following vowel) rather than in the noise portion of the fricative. The discovery that older adults are more likely to confuse [f] and [θ] than younger adults would be consistent with the hypothesis that perception of certain dynamic consonant cues (such as formant transitions) is vulnerable to the aging process.

In a more recent study, Elliott, Hammer, Scholl, and Wasowicz (1989) found significant age differences in the discrimination of synthetic single-formant transitions. In particular, Elliott et al. (1989) determined the smallest acoustic differences that could be discriminated between synthetic single-formant frequency transitions that simulated the second formants of voiced stop consonants. Results indicated that both children and older adults exhibited significantly poorer transition discrimination than did teenagers/young adults.[1]

Most studies on this topic have concentrated upon consonant recognition. In general, the literature has dealt much less with vowel recognition and certainly has not investigated the extent to which older listeners fail to process the *dynamic cues* that might underlie vowel perception. For example, Dorman et al. (1985) found no age-related difference in the identification of vowel quality in the context [b—t]. However, these tokens contained both relatively steady-state cues to vowel quality (i.e., the medial vowel itself) and the CV and VC formant transitions.

It has long been recognized that dynamic changes in spectral energy over time following the release of a consonant closure in CV syllables provide important information about place of articulation for that stop (Kewley-Port, 1983; Kewley-Port & Luce, 1984; Lahiri & Blumstein, 1981; Ohde & Stevens, 1983). There is also ample experimental evidence demonstrating the importance of such dynamic acoustic information in the perception of the vowel itself. First, several studies (e.g., Strange, Verbrugge, Shankweiler, & Edman, 1976; Verbrugge, Strange, Shankweiler, & Edman, 1976) have shown that a vowel produced in a CVC context can be identified as well as or better than isolated vowels, despite the fact that the consonantal context introduces coarticulatory variations in the vowel's formant frequencies (Lindblom, 1963; Stevens & House, 1963) that should tend to reduce vowel identification scores. Although some instances in which vowel identification is actually higher in context than in isolation may be an artifact of orthographic interference or stimulus-response compatibility (e.g., the labels on the response sheets match more closely the form of the tokens containing consonant context than the isolated vowels; see Diehl, McCusker, & Chapman, 1981; Macchi, 1980), no study has found that isolated vowels are consistently identified more accurately than vowels in a consonantal context.

Second, inherent spectral change has long been recognized as an important cue to the identification of diphthongs (Gay, 1970; Joos, 1948). However, studies by Assmann, Nearey, and Hogan (1982) and Nearey and Assmann (1986) support the suggestion that even in the case of isolated "monophthongal" vowels, inherent spectral change (that is, changes in formant frequencies over time associated with specific vowel qualities and independent of consonantal context) may play a significant role in vowel identification. For example, Nearey and Assmann (1986) presented listeners with two 30-msec acoustic sections gated from naturally produced vowels (extracted at positions corresponding to 24% and 64% of the total duration). Listeners were able to identify vowel quality on the basis of these two short sections as well as when the full vowel was heard—provided that the two sections were presented in their natural order. If the first section was repeated or the order of the sections reversed, identification scores decreased dramatically.

Finally, it has been shown that vowels in a CVC context can be identified reliably on the basis of formant transitions alone *without* quasi-steady-state formant pattern (Jenkins, Strange, & Edman, 1983; Strange, 1989; Strange, Jenkins, & Johnson, 1983). In these studies, it has been shown that vowels of naturally produced CVC syllables (such as [bɑb] and [bɪb]) could be reliably identified even when most of the medial vowel (up to 65%) had been replaced by silence (so-called *silent-center* tokens). In many cases the identification rates associated with the silent-center tokens were comparable to, if not lower than, those obtained when the medial vowel alone was presented. Fox (1989) demonstrated that listeners were able to identify the medial vowel in a synthetic [bɪb]-[bɛb] continuum with only 1 or 2 pitch periods of the CV and VC transitions present (the remainder of the CVC token being replaced by silence). On the other hand, identification of the medial vowel in isolation (without the dynamic acoustic changes at the syllable margins) with only 1 or 2 pitch periods was close to chance.

These studies have shown the importance of dynamic information in the identification of vowels by young adults, but no studies have shown the importance of such information to older adults. We postulate that age-related decrements in the ability to process auditory signals that change in time, such as formant transitions, will significantly affect older adult listeners' ability to use dynamic acoustic information in identifying vowel quality. The present study examines the ability of older adult listeners to identify the segments in CVC words in both silent-center and unmodified conditions.

Method

Subjects

Thirty-nine normally hearing adults participated in the study. Seventeen subjects between ages of 19 and 25 years

[1] It is quite possible that the perceptual change in processing dynamic acoustic information seen in older adults is a product of a more general developmental continuum throughout the life span. For example, researchers such as Elliott and her colleagues in a number of studies (Elliott, Busse, & Bailet, 1985; Elliott et al., 1979; Elliott & Katz, 1980; Elliott, Longinotti, Meyer, Raz, & Zucker, 1981) have demonstrated that both children and older adults show poorer performance in processing speech (using a variety of different experimental tasks and stimulus sets) than teenagers/young adults. However, it is doubtful that such perceptual decrements in children and older adults have the same etiology.

(mean age 21.1 years) and 22 older listeners between the ages of 61 and 75 years (mean age 66.9 years) participated in the experiment. All subjects were native speakers of American English. The young adults were undergraduate students in the Division of Speech and Hearing Science at Ohio State University and participated in the study to partially fulfill a class requirement. These students had just entered the major, were naive as to the purpose of the experiment, and had very limited experience with phonetics or speech science. The older adults were recruited from area senior citizen centers and were paid for their participation. The data from 1 young adult and 6 older adults were eliminated from this study (leaving 16 subjects in each age group) because their hearing sensitivity did not meet our criterion.

All subjects had normal equivalent ear-canal volume, tympanometric width, and peak compensated static acoustic admittance (ASHA, 1990). Contralateral acoustic reflexes were present bilaterally in all subjects (70–95 dB HL) at 1000 Hz. Hearing thresholds for 0.5, 1, and 2 kHz for all subjects did not exceed 25 dB HL (ANSI, 1970) in both ears. Mean right-ear pure-tone averages (PTA) for the young and older adult subjects were 1.9 and 10.1 dB HL, respectively. Average left-ear PTAs were 2.2 and 10.2 dB HL, respectively. In addition, all subjects had average thresholds at 4 kHz that did not exceed 35 dB HL. All older subjects had pure-tone thresholds of 25 dB HL at 4 kHz except for 2 older subjects, who had pure-tone thresholds of 25 dB HL or better at 3 kHz. Pure-tone thresholds for all subjects at octave frequencies from 0.25 to 8 kHz are shown in Appendix A. Although the two age groups differed significantly in hearing sensitivity at 8 kHz, the stimulus tokens used in this study had little or no acoustic energy above 4.5 kHz.

Central auditory function was screened using the Staggered Spondaic Word test (SSW) (Katz, 1962), performance intensity functions for monosyllabic words (PI-PB) (CID W-22) and Synthetic Sentence Identification (PI-SSI) with an ipsilateral competing message (SSI-ICM) (Jerger & Hayes, 1977), and the Pitch Pattern Sequence Test (PPST) (Pinheiro, 1977). For this study, normal central auditory function was defined as maximum performance for the PI-PB and the PI-SSI functions (85–100%) and a difference of less than 20% between the maximum PB performance and the maximum SSI performance; PPST normal range was 88–100%; and for the SSW (90–100%), emphasis was placed on the competing condition scores. Scores were not corrected for word recognition or response bias (Mueller, 1987).

Cognitive function was screened (28 correct out of 30 was passing) using the Mini Mental State test (Folstein, Folstein, & McHugh, 1975). Medical history, as self-reported, indicated that all subjects were right-handed and had no history of head injury or neurological disorder. Older subjects had at least a high school education (many had a college education) and were taking no medications known to affect neural/ auditory functioning. All were unfamiliar with the goal of the experiment.

Stimuli

The stimuli consisted of a set of 61 relatively common (i.e., high word frequency), familiar English monosyllabic words (a list of these tokens appears in Appendix B). All had a CVC syllabic structure. Word frequency for these stimuli ranged from 23 to 4329 occurrences per million (Kucera & Francis, 1967), with a mean word frequency of 248. The initial and final consonants used in constructing the stimulus list were stops or fricatives only ([b, d, g, p, t, k, ʃ, s, z]). Medial vowels included [i ɪ eɪ ɛ æ ɑ ɔ ʌ oʊ ʊ u aʊ aɪ ɝ]. Several exemplars of these words were spoken by a male speaker with a standard American English dialect and recorded using a high-quality microphone (Sony ECM-170), preamplifier (Nakamichi PS-100 and MX-100), and cassette tape deck (Nakamichi CR-2A). The speaker was a trained phonetician and maintained the same basic fundamental frequency contour over all words. These tokens were low-pass filtered at 4.8 kHz and digitally sampled at a 10-kHz sampling rate with 12-bit quantization onto a computer disk (PDP 11/23 system). Preliminary acoustic analyses of these words were done and one exemplar of each token selected for use in the stimulus set. All tokens were equalized with regard to mean squared amplitude of the medial vowel.

Two versions of these stimuli were created. One version corresponded to the unmodified token (whole token), including prevocalic voicing (if present). The start of the vowel was defined as the point of initial stop consonant release (if the token began with a voiced stop) or the start of periodicity following the aperiodic energy of an initial fricative (if the token began with a voiceless fricative). All initial voiced stops were prevoiced, but this acoustic energy was not considered part of the vowel. The end of the vowel was considered to be the onset of a final stop closure or the onset of the aperiodic energy for a final fricative. All final stops were released. Silent-center tokens were constructed by replacing all but six glottal pulses at the start or end of the vowel with silence.[2] This waveform editing procedure is similar to that used by Strange et al. (1983; Strange, 1989), who included three to five glottal pulses in the CV component and four to six glottal pulses in the VC component.

These initial and final portions of the vowel contained all of the CV or VC formant transitions, respectively, and very little steady-state vowel information. The silent-center tokens thus included both dynamic spectral cues (formant transitions) and durational cues (overall duration from vowel onset to offset) to vowel quality. Figure 1 shows the waveforms and spectrograms of the whole-token and silent-center versions of a representative stimulus token (*gate*). The total duration of the vowel, the CV and VC portions of the silent-center version, and the percentage of vowel replaced by silence for each of the 61 stimulus tokens are provided in Appendix B. The mean (total) vowel duration for the stimulus tokens was 282 msec. The mean CV and VC transitions left intact in the silent-center tokens were 44.3 and 52.3 msec, respectively. On the average, 62% of the vowel was replaced with silence in the silent-center condition.

[2]Instead of replacing the steady-state portion of the vowel with silence, we could have replaced it with a noise segment of equivalent duration and amplitude. Although this would have eliminated abrupt offsets and onsets, results obtained by Jenkins et al. (1983) and Parker and Diehl (1984) showed no improvements in identification scores when noise rather than silence was used.

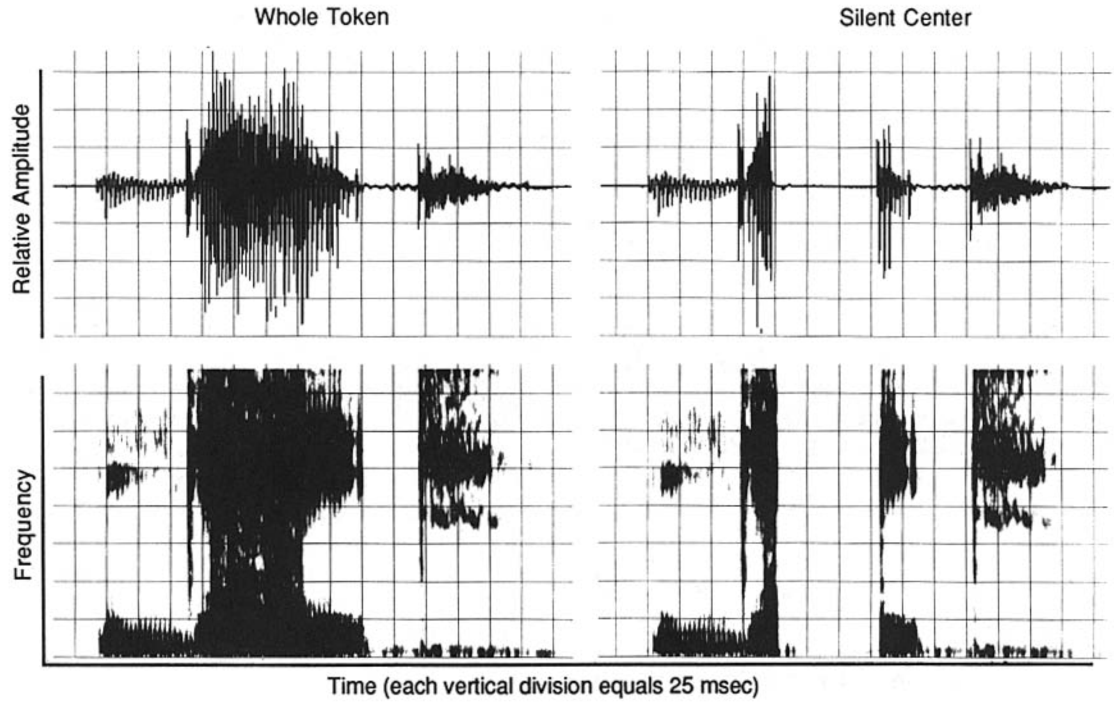

FIGURE 1. Waveforms (upper half of the figure) and spectrograms (lower half of the figure) of the whole-word (left) and silent-center (right) versions of the stimulus token *gate*. Vertical divisions along the frequency axis in the spectrograms represent 500 Hz. Note the prevoicing of [g] and the burst release of both the initial and final stops. The initial and final portions of the vowel not deleted in the silent-center version contain only the formant transitions.

Two audiotapes were constructed from these stimulus sets, one with the whole-word tokens and the other with the silent-center tokens, each one completely randomized. The digitized waveforms were played through a digital-to-analog converter at a 10 kHz sampling rate (12-bit quantization), low-pass filtered at 4.8 kHz, and recorded on a cassette recorder (Nakamichi CR-2A). There were 61 tokens on each tape, with an interstimulus interval of 6 sec. Preceding the test stimuli were a few samples of each type of stimulus: three repetitions of a whole word followed by three repetitions of the same word in its silent-center form. There were two of these sequences.

Procedure

Subjects sat in a sound-treated room (IAC 403) and listened to the stimulus tapes via headphones (TDH-49). Mean presentation level of the stimulus tokens was 75 dB SPL for the whole-word stimuli. The stimulus token amplitudes had been normalized prior to waveform editing; therefore, the amplitudes of the silent-center tokens were somewhat lower than those of the whole-word tokens because the high-amplitude syllable nuclei were reduced to silence (a difference also found in the stimuli used by Strange, 1989). Both sets of tokens had the same amount of acoustic energy at the dynamically changing syllable margins.[3]

Each subject heard the silent-center tokens first, followed by the whole-word tokens. Subjects were told that these tokens would represent common English words. For the silent-center condition, they were informed that the medial vowel had been removed and replaced with silence. In both stimulus conditions, subjects were required to say aloud the English word corresponding to the stimulus token (similar to the task found in Assmann et al., 1982). Because all stimuli represented common English words, subjects had relatively little difficulty in providing a spoken response. Guessing was encouraged if the subject was unsure of the word.

Subjects spoke into a microphone (Sony ECM-170), and their responses were heard through a sound-field speaker by an experimenter, who recorded the responses. The experimenter recording the responses was a certified speech-language pathologist experienced with and competent in narrow phonetic transcription. In general, if the vowel quality of the response was ambiguous between the intended vowel and a different vowel, it was considered to be a correct response. Listeners were given no explicit feedback during the experiment about individual stimulus items. There was a 5-min break between stimulus conditions.

We required subjects to provide spoken responses rather than written responses to reduce procedural difficulties associated with familiarizing listeners with a written task designed to identify vowel quality. In many studies in which

[3]The silent-center tokens were not "renormalized," because this would have disrupted this equivalence at the syllable margins. However, the most important goal in this study is the comparison of the results of the two age groups who are listening to the same sets of stimuli under identical task conditions.

TABLE 1. Mean percent correct identification scores for younger and older listeners in both silent-center and whole-word conditions.

	Whole token[a]		Initial consonant		Medial vowel		Final consonant	
Condition	Y	O	Y	O	Y	O	Y	O
Overall	90.5	84.5	99.6	95.5	91.7	88.0	98.2	94.8
Silent-center	83.8	73.6	99.7	92.6	85.3	78.1	96.7	90.9
Whole-word	97.2	95.3	99.4	98.3	98.1	97.9	99.6	98.7

Note. Y = younger listeners (19–25 years old); O = older listeners (61–75 years old).
[a]Whole-token scores reflect the percentage of times subjects identified all three segments correctly.

subjects must circle response items (such as *hid, head, had*) containing the same vowel as the stimulus items, extensive subject training with the response procedure is required, with no guarantee of success. As Strange (1989) noted, even after extensive task familiarization, some subjects (all were young adults in her study) were eliminated because they could not keep up with the task of finding and recording the proper entry on the response form. This written task would have been more difficult in the present experiment because we had a larger number of vowel qualities than either Strange et al. (1983) or Strange (1989). In addition, given the general tendency toward slower performance (mental and physical) in older adults (Bashore, Osman, & Heffler, 1989), the written task might well have been even more difficult for the older subjects to master.

There is experimental evidence that the spoken response task, such as that used here, is an appropriate instrument for a vowel identification test. A study by Diehl et al. (1981) required subjects to identify the medial vowel in CVC tokens (similar to the whole-word tokens in the present study) and in isolation. One group of subjects provided written responses by circling the "word" on their answer sheets corresponding to the stimulus token. A second group of listeners provided a spoken response by "mimicking" the stimulus token. A third group of listeners were provided with response sheets containing vowel labels (e.g., EE, Ā). Diehl et al. found that identification errors rates in the mimicking condition were significantly smaller than in the two written response conditions.[4]

Results

The identification scores for both the silent-center and whole-word conditions are given in Table 1. Incorrect scores included both misidentifications and omissions. (There were relatively few omissions, and they occurred only among the older adult subjects.) Confusions between [ɑ] and [ɔ] were not counted as errors because this distinction does not occur in the Midwestern dialect of American English spoken by our subjects. The percentage data were converted to arcsine transforms for all statistical tests described below.

In general, older adult subjects showed somewhat poorer identification scores. Age-related differences were greatest in the silent-center condition. A two-way repeated-measures analysis of variance of the word identification scores (i.e., entire token correctly identified) with the between-subject factor age (younger and older) and the within-subject factor stimulus condition (silent-center and whole-word) showed significant main effects of age [$F(1, 30) = 7.31$, $p < .02$] and stimulus condition [$F(1, 30) = 230.5$, $p < .001$]. The interaction effect between age and stimulus condition was not significant [$F(1, 30) = 2.01$, $p > 0.16$].

However, although the word-correct measure provides some information about the ability of the subjects to utilize dynamic acoustic information, it does not provide information as to which segments in the CVC tokens are most difficult to identify, or which segmental errors produced the incorrect word response. A three-way repeated-measures analysis of variance of the individual segment data with the between-subject factor age and the within-subject factors stimulus condition and segment (initial consonant, medial vowel, and final consonant) showed significant main effects of age [$F(1, 30) = 10.2$, $p < .003$], stimulus condition [$F(1, 30) = 141.0$, $p < .001$], and segment [$F(2, 60) = 66.7$, $p < .001$]. Both the Age × Stimulus Condition [$F(1, 30) = 6.69$, $p < .015$] and the Stimulus Condition × Segment [$F(2, 60) = 48.8$, $p < .001$] interactions were significant. Neither the Age × Segment nor the Age × Segment × Stimulus condition interaction was significant. The significant segment effect was obtained because for both groups of subjects the identification of the medial vowels was worse than for both the initial and final consonants. Post hoc Bonferroni *t* tests showed no significant difference in the identification scores for initial and final consonants. However, both sets of consonant identification scores were significantly higher ($p < .001$) than the vowel identification scores. One-way analyses of variance with the between-subject factor age showed a significant age effect in the identification of both initial [$F(1, 30) = 15.3$, $p < .001$] and final consonants [$F(1, 30) = 4.2$, $p < .05$] in the silent-center condition but no significant age effect for either initial [$F(1, 30) = 2.4$, $p > 0.13$] or final consonants [$F(1, 30) = 3.09$, $p > .08$] in the whole-word condition.

The identification of vowel quality was most affected by the silent-center condition for both groups of subjects, but a similar pattern of age effects was obtained. In particular, in the silent-center condition, there was a significant age effect [$F(1, 30) = 5.3$, $p < .03$]. However, there was no significant age difference in the whole-word condition [$F(1, 30) = .51$,

[4]However, as an anonymous reviewer pointed out, the mimicking procedure used by Diehl et al. (1981) was somewhat different than the procedure used here. Diehl et al. tape-recorded subject responses and obtained interjudge reliability measures from the three phonetically trained listeners who transcribed these responses. Their version of the verbal response task may thus provide more dependable information about subject performance, especially when subtle vowel quality differences are encountered. In the transcription procedure used here, a vowel was judged as "correct" (i.e., the same as the intended vowel) whenever it was ambiguous—a procedure likely to have underestimated the number of subject errors for both age groups.

TABLE 2. Mean percent correct vowel identification scores for younger and older listeners in both stimulus conditions broken down by vowel type.

	Monophthongs		Diphthongs		Rhotic vowels	
Condition	**Y**	**O**	**Y**	**O**	**Y**	**O**
Overall	92.6	88.6	87.8	86.4	98.4	90.7
Silent-center	87.3	79.5	76.1	72.7	96.9	81.3
Whole-word	97.8	97.6	99.5	100.0	100.0	100.0

Note. Y = younger listeners (19–25 years old); O = older listeners (61–75 years old).

$p > .48$]. Although both groups of subjects correctly identified vowel quality most of the time in the whole-word condition (the difference between the two groups in mean correct scores was only 0.2%), older adult subjects were significantly worse in identifying vowel quality on the basis of dynamic information alone (in the silent-center condition the mean identification score for older adults was 7.2% lower).

Although the hearing sensitivity of the two age groups was relatively well matched at .25–2 kHz, there was a somewhat greater difference in the 4 kHz thresholds. Because the tokens have acoustic energy up to 4.8 kHz, it is important to determine whether this sensitivity difference contributed to the ability to identify the vowels in the silent-center condition. A one-way analysis of variance with the between-subject factor age was done on the vowel identification data in the silent-center condition with the right ear thresholds at 4 kHz as a covariant. There was a significant effect of age [$F(1, 29) = 4.68$, $p < .04$], but there was no significant relationship between the 4 kHz thresholds and the responses.

Although all stimulus tokens represent common American English words, there was some variation among the tokens in terms of word frequency. To determine whether word frequency had a significant influence on vowel identification, correlations (Pearson's r) were calculated between word frequency (in occurrences per million from Kucera & Francis, 1967) and percentage correct vowel identification in both the silent-center and whole-word conditions. None of the correlations was significant.

Table 2 gives a breakdown of vowel identifications in terms of vowel type: monophthongal (e.g., [i ɪ ɛ u ʊ], diphthongal (e.g., [aɪ aʊ eɪ]), and rhoticized ([ɚ] as in *bird*). The two groups of subjects were most accurate identifying the rhotic vowels in both the whole-word and silent-center conditions. The lowered third formant in rhotic vowels easily distinguishes them from all other vowels in American English (Singh & Woods, 1971). As might be expected, the diphthongs were the most difficult to identify in the silent-center condition. This no doubt stems from the fact that the silent-center diphthong stimulus begins with one vowel quality and ends with another, but the transitional center portion has been replaced with silence.

A three-way repeated-measures analysis of variance with the factors age, stimulus condition, and vowel type showed a significant main effect of vowel type [$F(2, 60) = 40.6$, $p < .001$] in addition to the significant stimulus type effect [$F(1, 30) = 127.3$, $p < .001$]. There was also a significant Stimulus Type × Vowel Type interaction [$F(2, 60) = 27.1$, $p < .001$]. These results merely show that all the vowel types are identified accurately in the whole-word condition, but diphthongs and monophthongs are identified more poorly than rhotic vowels in the silent-center condition. There was no significant Age × Vowel Type interaction, indicating no significant difference between the two age groups in their error patterns for vowel identification.

Shown in Tables 3 and 4 are the vowel confusion matrices obtained in the silent-center condition (there were not enough errors in the whole-word condition to create a useful confusion matrix). The general pattern of vowel confusions shows few differences between the two age groups except that the older subjects sometimes refused to provide a response (1.3% of the time). Both groups of subjects tended to misidentify the silent-center vowels as lax vowels ([ɪ ɛ ʌ]).

TABLE 3. Vowel confusion matrix for younger subjects in silent-center condition.

	i	ɪ	eɪ	ɛ	æ	ɚ	ʌ	ɑ	ɔ	oʊ	ʊ	u	aɪ	aʊ
i	127	1	16											
ɪ		56		22	2									
eɪ		4	116	1			6						1	
ɛ		2		57	5									
æ				8	104									
ɚ						31				1				
ʌ		1		1			38		8					
ɑ					6		5	80	1	1	2			
ɔ							5	1	57		1			
oʊ										29	3			
ʊ				3				2			75			
u												32		
aɪ		2	2	12	1		4	1			6		20	
aʊ				3			1	1	2					9

Note. Rows show intended vowel quality; columns show vowel responses.

Discussion

The aim of this study was to compare the ability of younger and older adult listeners to identify English monosyllables (CVCs) in two conditions: when the entire word was presented and when a large percentage of the medial vowel had been replaced by silence. The findings revealed several different points.

First, both older and younger adult subjects performed significantly better identifying the whole-word than the silent-center tokens. These data differ from the results described in Jenkins et al. (1983), who found no significant difference between the control stimuli (unedited [b]+vowel+[b] syllables) and their corresponding silent-center versions. However, in the present study, the control tokens and the edited silent-center versions represented different examples of real English words. Subjects heard the silent-center version of each token before they were required to identify any of the whole-word tokens (i.e., the stimulus condition factor was a within-subject factor). Subjects in the whole-word condition thus had had experience with the stimulus set and could be expected to perform better (a type of lexical priming). In fact, the identification results in the whole-word condition may have reached ceiling, thus obscuring any slight age-related perceptual difference between the two groups of subjects.

Second, there was a significant difference in the two age groups in the identification of vowels in the silent-center condition. Older adults made more errors in identifying words with all three types of vowels (monophthongs, diphthongs, and rhotic vowels) than did the young adults, although the age differences were the smallest in identifying tokens with medial diphthongs. These data would support the hypothesis that older listeners are poorer, in general, at utilizing dynamic acoustic information in identifying speech tokens. However, this study did not address the difference between age groups in identifying isolated vowels. It is quite possible that older adults are less able to identify isolated vowels (without surrounding consonantal context), as well, given the results described in Nittrouer and Boothroyd (1990). Nittrouer and Boothroyd demonstrated that phoneme recognition scores for both young adults and older adults were higher when the token represented a real word rather than a nonsense syllable; scores for the nonsense syllables were significantly lower for the older adults. These results suggested that older adults depended upon contextual information (in the form of lexical constraints) more than did young adults. In the present study, all tokens represented real English words and thus no word context effect should be expected, but we did not find any effect of word frequency that might be considered a type of lexical constraint. If this study had included isolated vowels (which, for the most part in English, represent nonsense syllables), a word context effect might have appeared.

Third, the pattern of vowel misidentifications (seen in the confusion matrices) was similar between the two groups, except that the responses of the older adults included many more examples of the lax vowels [ɪ] and [ɛ], and these older subjects refused, on occasion, to make a response. Both groups tended to confuse [ɪ] and [ɛ] and identified the diphthong [aɪ] as [ɛ]. However, the similarity in the pattern of misidentifications would suggest that older adults are not processing the relevant acoustic information significantly differently from the young adults.

Finally, there was also a significant difference in the two age groups in the identification of both initial and final consonants in the silent-center condition (a difference of 6–7%). This difference was not as large as that found by Dorman et al. (1985), but there is an important difference between the stimuli used by Dorman et al. and those used in the present study. Subjects in the Dorman et al. study heard CV nonsense tokens (a [bɑ-dɑ-gɑ] continuum) that were synthesized with only two formants. These tokens had no release burst, and none of the tokens was prevoiced. However, the stop release bursts found in natural speech contain important dynamic acoustic cues to place of articulation. These cues include spectral tilt for distinguishing between labials and alveolars and midfrequency peaks important to the identification of velars (Blumstein & Stevens, 1979, 1980; Kewley-Port, 1983; Kewley-Port & Luce, 1984). Dorman et al. (1985) attributed the reduced performance of their normal-hearing older listeners to "an inability to base phonetic identification on dynamic spectral cues when other cues, which normally characterize a phonetic segment [such as the release burst cues], are unavailable for use" (p. 669). The fact that normal-hearing older listeners had greater difficulty

TABLE 4. Vowel confusion matrix for older subjects in silent-center condition.

	i	ɪ	eɪ	ɛ	æ	ɚ	ʌ	ɑ	ɔ	oʊ	ʊ	u	aɪ	aʊ	ɔɹ	aɹ	NR
i	102	3	37	1													1
ɪ		51	5	20	2		1										1
eɪ		9	110				4					1					4
ɛ		4		49	10												1
æ		1	1	12	98												
ɚ		2				26									2	2	
ʌ		3		1	1		30	1	12								
ɑ		3		5	1		2	81			1						3
ɔ		1					3	2	55	1					1	1	
oʊ		4		1						20	7						
ʊ		5					1	2			72						
u		1										31					
aɪ		6		10							2		27				2
aʊ		1		2			2							10			1

Note. Rows show intended vowel quality; columns show vowel responses. NR indicates no response.

in identifying the stop consonants in the silent-center condition when the tokens were constructed from natural speech would suggest that additional factors are involved in this age-related perceptual decrement. These additional factors seem to involve the processing of dynamically changing acoustic information while making either vowel or consonant identifications in the perception of speech.

Strange (1989) discussed two possible hypotheses about the nature of the dynamic information specifying vowel identity. The first was the "spectral change" hypothesis, which suggested that silent-center tokens contain sufficient information about the direction and/or slope of vowel-inherent spectra change necessary for correct identification of both monophthongal and diphthongal vowels (see studies by Nearey, 1989; Nearey & Assmann, 1986). The second was the "temporal trajectory" hypothesis, which suggested that the temporal structure of the formant trajectories in the CV and VC transitions are closely associated with the temporal characteristics of the articulatory gestures of the coarticulated CV or VC syllable margins and provide critical perceptual information for vowel identity (see Di Benedetto, 1989; Huang, 1986). Both hypotheses assume that listeners are able to extract frequency-dependent acoustic information from the acoustic waveform that may change quickly in time.

How might an age-dependent decrement in processing such dynamic information be explained? One possible factor involves age-related changes in sensory processing abilities, particularly in terms of decreased frequency resolution ability (see Lutman, Gatehouse, & Worthington, 1991; Patterson, Nimmo-Smith, Weber, & Milroy, 1982). If older adults have decreased ability to discriminate among frequencies, one should except a decreased ability to process the dynamic acoustic information contained in the CV and VC transitions even when the older adult subject has good detection of pure tones. Another factor might involve age-related changes in slowing of mental processes (Bashore et al., 1989; Salthouse & Kail, 1983). For example, a number of studies have shown that cognitive processes as measured with electrophysiological measures, such as the latency of the P300, slow with age (Goodin, Squires, Henderson, & Starr, 1978; Wall, Fox, Moenter, & Dalebout, 1991; Woodruff, 1982). If older adults process signals less rapidly than young adults, it is reasonable to assume that they would perform less efficiently even in the absence of a peripheral hearing loss; and if older adults need more time to process signals, then the ability to process dynamic acoustic information contained in the formant transitions would be degraded. Although it is almost certainly the case that no single factor underlies the age-related decrement in processing dynamic acoustic information discussed here, given the importance of spectral change in signaling phonetic distinctions, it is important to continue to investigate this possible source of speech processing difficulties in the aging population.

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Appendix B

Pure-tone thresholds for all subjects at octave frequencies between .25 and 8 khz in the left ear (L) and the right ear (R). If one of the thresholds was greater than 25 dB at 4 kHz, the threshold at 3 kHz was measured. The last two columns show the pure-tone averages (at .5, 1, and 2 kHz) for each ear. Values are in dB HL.

Subject number	Frequency														PTA Left	PTA Right
	.25 kHz		.5 kHz		1 kHz		2 kHz		3 kHz		4 kHz		8 kHz			
	L	R	L	R	L	R	L	R	L	R	L	R	L	R		
Younger subjects																
1	0	15	0	5	0	0	0	0	—	—	0	0	10	15	0	1.7
2	0	0	0	0	0	0	−5	0	—	—	0	10	5	15	−1.7	0
3	5	5	0	0	0	0	0	0	—	—	0	0	10	10	0	0
4	10	5	5	0	0	0	0	0	—	—	10	10	10	15	1.7	0
5	10	10	5	5	0	5	0	0	—	—	10	0	10	0	1.7	3.3
6	5	15	5	10	0	0	0	0	—	—	0	0	0	0	1.7	3.3
7	10	5	10	5	0	0	0	0	—	—	5	10	10	15	3.3	1.7
8	10	15	0	5	10	5	0	0	—	—	0	0	5	10	3.3	3.3
9	5	5	0	0	0	0	0	0	—	—	5	0	0	0	0	0
10	5	15	0	15	0	5	0	0	—	—	5	5	0	0	0	6.7
11	15	10	10	5	0	0	0	0	—	—	5	5	0	0	3.3	1.7
12	10	15	5	10	5	0	5	−5	—	—	5	5	5	10	5	1.7
13	5	0	0	5	5	0	0	0	—	—	5	5	0	10	1.7	1.7
14	5	10	5	5	10	0	5	10	—	—	0	5	0	0	6.7	5
15	5	5	5	5	0	0	0	0	—	—	5	0	0	0	1.7	1.7
16	10	15	5	10	0	0	0	0	—	—	0	0	5	5	1.7	3.3
M	6.9	9.1	3.4	5.3	1.9	0.9	0.3	0.3	—	—	3.4	3.4	4.4	6.6	1.9	2.2
Older subjects																
1	5	5	10	0	10	10	5	5	—	—	20	20	60	50	8.3	5
2	15	10	15	15	10	15	5	10	—	—	5	15	50	35	10	13
3	5	0	10	5	10	15	20	15	—	—	30	25	35	30	13.3	12
4	5	0	0	0	0	5	0	5	—	—	10	5	30	15	0	3.3
5	10	10	10	5	10	10	20	10	—	—	5	10	15	30	13.3	8.3
6	10	10	10	10	5	15	0	0	—	—	10	15	35	35	5	8.3
7	20	25	15	20	20	20	10	15	—	—	0	5	10	15	15	18
8	5	0	5	0	5	0	0	5	—	—	5	10	20	10	3.3	1.7
9	5	5	5	10	10	10	10	0	—	—	15	0	45	40	8.3	6.7
10	10	20	10	15	10	10	15	15	—	—	20	20	20	20	11.7	13
11	15	20	10	10	10	5	15	20	20	25	35	35	60	55	11.7	12
12	10	15	10	5	15	15	20	15	20	25	30	40	50	50	15	12
13	0	20	5	20	10	20	0	25	—	—	20	35	45	80	5	22
14	15	10	10	0	20	15	20	15	—	—	15	15	10	20	16.7	10
15	10	15	15	10	15	10	10	15	—	—	15	25	15	25	13.3	12
16	20	10	20	5	10	0	5	15	—	—	5	15	60	30	11.7	6.7
M	9.7	10.9	10.0	8.1	10.6	10.9	9.7	11.6	—	—	15	18.1	35	33.8	10.1	10.2

Total vowel duration, CV and VC transition duration, and silent-center durations for all 61 stimulus tokens (duration values are in msec).

Token	Vowel duration	CV duration	VC duration	Silent center duration	% vowel replaced with silence
bag	442	38	55	349	79
Bob	474	45	55	374	79
bird	394	46	54	294	75
bit	200	56	67	77	39
beg	295	43	53	199	67
beat	230	48	64	118	51
bed	328	46	56	226	69
bad	444	38	58	348	78
back	254	47	49	158	62
but	193	45	51	97	50
bought	251	47	51	153	61
boat	234	48	64	122	52
book	167	61	49	57	34
dip	220	46	45	129	59
did	340	60	60	220	65
dead	365	64	62	239	65
dog	433	57	51	325	75
dirt	240	62	47	131	55
get	218	67	46	105	48
God	448	64	54	330	74
got	279	71	52	156	56
good	362	52	53	257	71
date	270	50	59	161	60
doubt	316	60	48	208	66
died	465	60	54	351	75
gate	271	52	53	166	61
guide	466	56	53	357	77
sit	153	39	49	65	42
sick	135	38	47	50	37
seat	200	39	56	105	53
seek	157	37	46	74	47
set	180	39	41	100	56
sat	240	39	48	153	64
sought	241	38	48	155	64
seed	327	36	59	232	71
sad	404	40	54	310	77
suit	181	38	47	96	53
she'd	331	32	49	250	76
sheep	208	39	47	122	59
shop	246	34	51	161	65
shot	219	34	52	133	61
should	292	33	51	208	71
shook	172	38	50	84	49
sheet	190	40	54	96	51
shock	225	41	50	134	60
shoot	197	41	49	107	54
sake	189	34	48	107	57
site	248	40	47	161	65
shape	218	38	48	132	61
showed	372	40	53	279	75
does	475	43	56	376	79
piece	214	31	53	130	61
pass	268	42	51	175	65
cause	433	39	54	340	79
bus	228	37	48	143	63
cash	282	33	53	196	70
push	178	37	53	88	49
base	266	42	52	172	65
days	494	34	62	398	81
case	243	33	42	168	69
pace	224	33	56	135	60
M	282.44	44.26	52.25	185.93	62

Age-Related Differences in Processing Dynamic Information to Identify Vowel Quality

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